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(71) Applicant: Hewlett-Packard Company  
3000 Hanover Street  
Palo Alto California 94304(US)

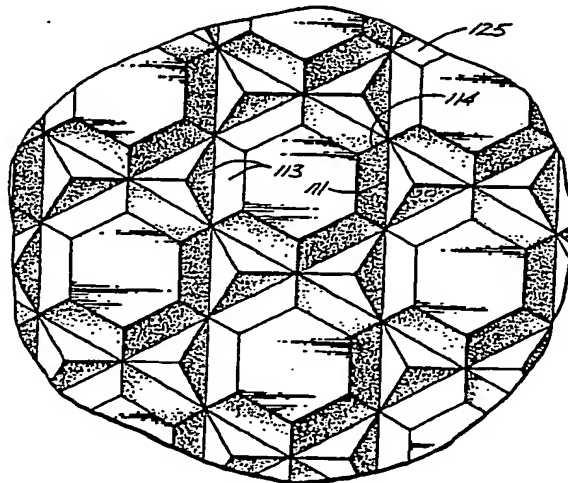
(72) Inventor: Haltz, Roland H.  
25 Adair Lane  
Portola Valley, California 94025(US)

(74) Representative: Colgan, Stephen James et al  
CARPMAELS & RANSFORD 43 Bloomsbury  
Square  
London WC1A 2RA(GB)

(64) High efficiency light-emitting diode.

(57) A transparent light-emitting diode has front (14) and back (12) parallel faces and a plurality of side faces (11) perpendicular to the back face. Diagonal faces (13) interconnect each side face (11) with the front face (14) to form a truncated polygonal pyramid surmounting a polygonal base of the light-emitting diode. Because some of the light impinges on the diagonal faces (13) at an angle less than the critical angle for total internal reflection ( $\theta_c$ ), from 1.5 to 2 times as much light is extracted from the LED as a conventional rectangular LED without the diagonal faces. The diagonal faces (13) on the LEDs are readily made by sawing V-shaped grooves in the front face of a wafer (21) on which the LEDs are fabricated.

Fig. 3



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non-escape directions into the escape cones. Some light within the escape cones may be internally reflected from a roughened surface. Further, the randomizing of the light directions requires many reflections and because of the non-negligible level of absorption, the long light path within the LED results in only a modest increase in extraction efficiency.

5 Taken to its ultimate or optimal configuration for light extraction, a LED would have a surface of a hemisphere so that light from a small p-n junction in its center is normal to the surface regardless of the ray direction. Such hemispherical LEDs have been built and are highly efficient, but extremely high in price because of the complex processing required. Some of such prior hemispherical LEDs were made by temporarily connecting two LEDs together base-to-base, then tumbling them in a rotating polishing mill until  
10 spherical. Alternatively, some of the prior hemispherical LEDs were made by attaching the LED chip to a dop and polishing much as one would polish a lens. The cost of LEDs made by such techniques is prohibitive for most applications.

It is, therefore, desirable to provide means for improving the efficiency of light extraction from an LED. It is also desirable that the technique be one easily implemented in manufacturing operations for LEDs  
15 without significantly decreasing the yield of LED chips from a wafer of semiconductor.

### Brief Summary of the Invention

20 There is, therefore, provided in practice of this invention according to a presently preferred embodiment a transparent light-emitting diode formed of a body of semiconductor material having a flat back face. A plurality of side faces extend perpendicular to the back face. These are surmounted by a plurality of diagonal faces with the number of diagonal faces being the same as the number of side faces. The resulting pyramid is truncated by a front face parallel to the back face. Electrical contacts are made with the  
25 back and front faces and a p-n junction within the semiconductor body emits light.

Such an LED may have essentially twelve escape cones, and internal reflections of light which does not escape in the first pass has a reasonable probability of being reflected into an escape cone. This provides an improvement in extraction efficiency of up to twice the light from a conventional LED.

### Brief Description of the Drawings

30 These and other features and advantages of the present invention will be appreciated as the same becomes better understood by reference to the following detailed description of a presently preferred embodiment wherein:  
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FIG. 1 is an exemplary transverse cross section of a light-emitting diode constructed according to principles of this invention;

FIG. 2 illustrates in transverse cross section a technique for cutting a semiconductor wafer for forming a plurality of light-emitting diodes;

40 FIG. 3 is a fragmentary plan view of one face of a wafer from which light emitting diodes are cut; and  
FIG. 4 illustrates in transverse cross section another embodiment of light-emitting diode.

### Detailed Description

45 A light-emitting diode (LED) is in the form of a body 10 of semiconductor material such as gallium arsenide, gallium phosphide,  $\text{GaAs}_{1-y}\text{P}_y$  or the like. In practice of this invention the LED has a rectangular base with four side faces 11 perpendicular to the back face 12 of the LED. In a typical embodiment the base is square. The base is surmounted by a truncated rectangular pyramid having four diagonal faces 13  
50 and a front face 14 parallel to the back face. A portion of the front face has a layer of metal 16 such as aluminum or a gold-germanium alloy for making electrical contact to the LED.

Electrical contact is made to the bottom of the LED by way of a metal layer 17 such as a gold beryllium alloy. Most of the back contact 17 is insulated from the body of semiconductor by an intervening dielectric silica layer 18. The back metal layer makes electrical contact through an aperture in the silica layer to a  
55 layer 19 of p-type material in the body of semiconductor which is primarily n-type material. Light is emitted from the resulting p-n junction and is transmitted through the semiconductor material which is transparent to the emitted wave length.

For purposes of description of the improved extraction efficiency, it is assumed that light is emitted

a conventional dicing saw aligned with the bottom of the groove to cut the balance of the distance through the wafer. In still another alternative the face of the dicing saw may be dressed so that the V-shaped groove and the parallel-sided cut through the balance of the wafer are made in a single pass of the dicing saw. After sawing, the sawed surfaces are etched for removing the highly absorbing saw damaged material adjacent to the surface.

It will be noted that cleaving produces side faces 11 of the LEDs which are substantially specular. The diagonal faces are slightly roughened due to the diamond particles in the dicing saw. The side faces are also slightly roughened when the LEDs are separated from each other by sawing. The resultant non-specular reflection of light from such faces slightly enhances efficiency of light extraction from the LED.

The square LED with beveled edges hereinabove described is a better approximation of a hemisphere than the rectangular parallelepiped of a conventional LED. A still better approximation of a hemispherical external shape is provided by a sawing pattern as illustrated in FIG. 3 which is a plan view of a fragment of a wafer with an array of V-shaped grooves cut in the front surface for separating individual LEDs from each other. As illustrated in this embodiment, each LED has a hexagonal front face 114 and six diagonal faces 113 adjacent six side faces 111 of the LED. The diagonal faces on the several LEDs on the wafer are defined by sawing a plurality of V-shaped grooves 125 at 60° from each other in the front face of the wafer.

The individual LEDs may then be separated from each other by cleaving from the bottom of the grooves or by extending a dicing saw cut clear through the wafer as hereinabove described. The latter technique is preferred since the crystal structure of the semiconductor does not lend itself to crystallographic cleavage at 60° angles and there is no problem in removing the triangular scraps between adjacent LEDs. It will be noted that because of such scraps the yield of hexagonal LEDs from a wafer is two-thirds of the yield of rectangular LEDs. The enhanced light extraction efficiency through twelve faces as compared with eight faces in the rectangular embodiment may offset the added cost due to decreased yield.

FIG. 4 illustrates in transverse cross section another embodiment of LED for high efficiency light extraction. This LED has side faces 211 and a back face 212 similar to the embodiments hereinabove described. It differs, however, in that one of the diagonal faces 213a is at a different angle from its adjacent side face 211 than the angle between the opposite side face 213b and its adjacent side face. A similar asymmetry is provided for the other two diagonal faces not illustrated in the drawing. As a result of this asymmetry, the front face 214 is shifted diagonally toward one corner of the LED.

The angular difference between the opposite faces is only a few degrees so that there is little degradation of the light extraction efficiency due to an exit cone of light illuminating an area off of a diagonal face. Substantial degradation may be avoided by choice of dimensions of the side faces and diagonal faces. However, extraction efficiency of light internally reflected within the LED is enhanced due to the asymmetrical reflections from the diagonal faces.

Such an embodiment with asymmetrical beveling is easily made by the technique described hereinabove by simply dressing the face of the dicing saw with the desired asymmetry, thereby producing an asymmetrical V-shaped groove.

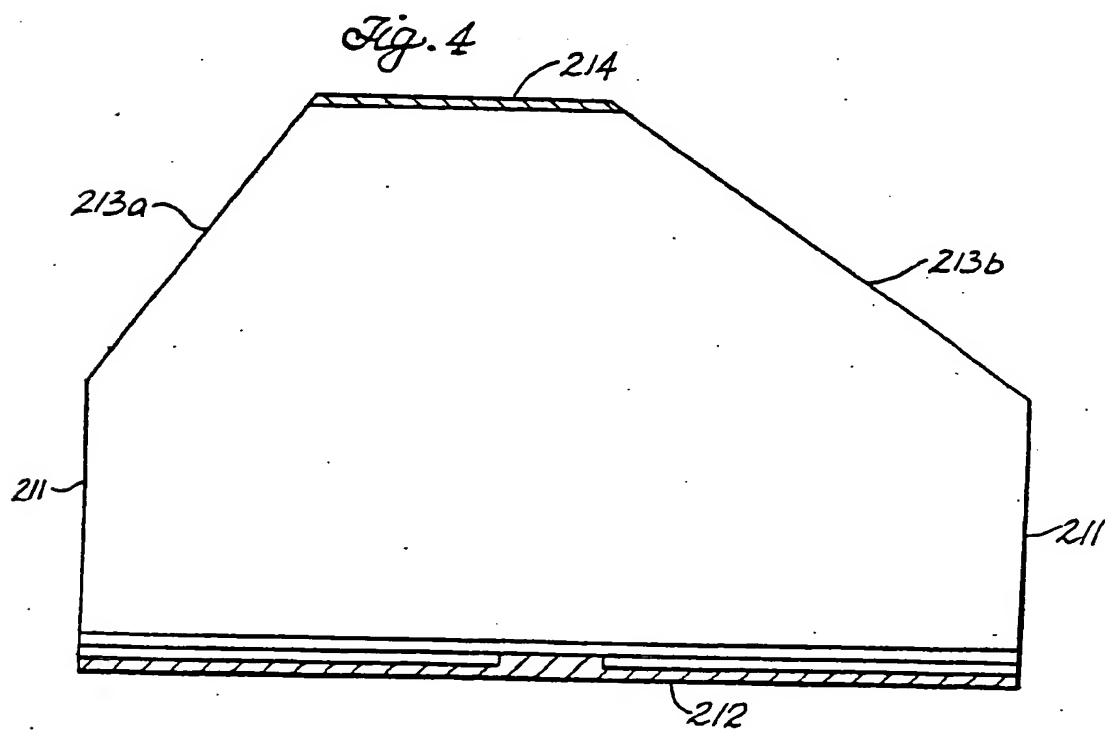
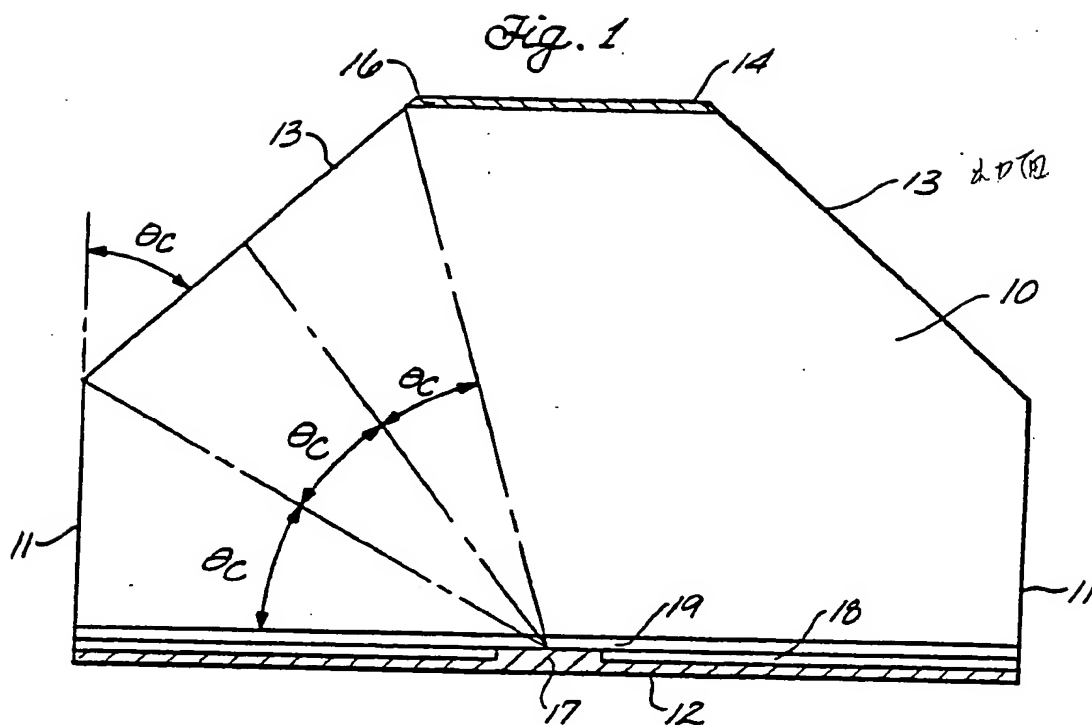
Although limited embodiments of light-emitting diode constructed according to principles of this invention have been described and illustrated herein, many modifications and variations will be apparent to those skilled in the art. Thus, for example, in the illustrated embodiments the p-n junction is quite near the back face of the LED. It may be desirable to employ a LED where the p-n junction is an appreciable distance above the back face. In such an embodiment it is preferable that the height of the side faces should subtend an angle above the center of the junction in the order of the critical angle for total internal reflection. Thus, half of the light in the exit cone is above the plane of the junction and some of the light may exit the side face below the plane of the p-n junction.

It will also be apparent that other polygonal shapes such as triangular or octagonal LEDs may be provided in practice of this invention. It is, therefore, to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

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## Claims

1. A transparent light-emitting diode comprising:  
a back junction (17);  
a front electrical contact (16); and  
a body (10) of transparent semiconductor between the back junction and the front electrical contact, the body being in the form of a polygonal base (11) surmounted by a truncated polygonal pyramid (13).
2. A light-emitting diode according to claim 1 wherein the base is rectangular with side faces (11)



*Fig. 3*

